

Three-dimensional Analysis of Wave Transmission and Sheltered Area of Floating Breakwaters

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Abstract

The growing demand for renewable energy has driven advancements in ocean exploration technologies involving floating structures. These structures are exposed to waves, requiring careful design to ensure safety. To enhance protection, the present research focuses on floating breakwaters designed to mitigate wave action. When considering regular waves, the wave transmission coefficient (K_t) for two-dimensional (2D) box-type floating breakwaters is well-defined in the literature. However, the wave transmission coefficient computation for three-dimensional (3D) floating breakwaters still requires a standardized method. In this context, this study conducts a parametric analysis of a box-type floating breakwater, using numerical models based on potential flow theory to determine the 3D wave transmission coefficient. Results reveal that, unlike 2D cases, different K_t levels emerge for a given 3D scenario. These findings suggest that breakwaters featuring high relative breakwater beam ratios are likely to present convergent mean wave transmission coefficients. Furthermore, the research demonstrates that the wave-shelter area is highly dependent on the breakwater beam ratio, with larger ratios leading to lower K_t levels. The sheltered area changes exponentially with the K_t levels. In addition, a practical application is introduced, leveraging machine learning techniques to predict the wave-shelter area and optimize breakwater dimensions. The proposed design minimizes construction costs while ensuring effective wave attenuation for a one megawatt-peak floating solar photovoltaic system. These findings enhance understanding of the wave transmission coefficient for 3D floating breakwaters, highlighting that variations in breakwater dimensions and wave conditions significantly influence the sheltered area, which impacts the protection of offshore structures.

Keywords Breakwater; Wave transmission coefficient; Machine learning; Offshore structure protection; Renewable energy

1 Introduction

Climate change and globalization have heightened social expectations for improved use of renewable energy sources

Article Highlights

- 3D scenarios reveal multiple K_t levels within the wave-shelter zone, a phenomenon attributed to destructive and constructive scattered wave interferences, unlike 2D cases.
- The wave-shelter area is highly dependent on the breakwater beam ratio, with larger ratios leading to lower K_t levels and thus enhanced wave protection.
- Higher relative breakwater beam ratios result in convergent mean K_t values. Additionally, the rectangular sheltered area exhibits an exponential relationship with K_t levels.
- Machine learning techniques are applied to predict wave-shelter areas and optimize breakwater dimensions, enabling cost-effective design for offshore structures, such as a one-megawatt-peak floating solar photovoltaic system.

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(Tavakoli et al., 2023). As a result, different ocean exploration technologies have been developed and studied as potential contributors to renewable energy generation. Floating structures play a crucial role in this exploration. However, given their exposure to wave forces, meticulous design is necessary to ensure safe operational windows. However, in some cases, design alone is insufficient to achieve the desired response, requiring additional floating structures to support wave mitigation. Floating breakwaters offer exceptional protective capabilities, not only shielding these floating structures but also safeguarding marinas, ports, fragile beaches from erosion, and coastlines from degradation (Dai et al., 2018). The earliest known floating breakwater, constructed from wood, was built at Plymouth Port in England in 1811 (Sawaragi, 1995).

Variations in shape, structural format, and design concepts lead to a diverse classification of breakwaters. First, considering wave attenuation mechanisms, Sawaragi (1995) classified floating breakwaters into three types: reflection, reflection and wave breaking, and friction-based type structures. Second, in terms of shape, Dai et al. (2018) classified the floating breakwater into seven categories: box, pontoon, frame, mat, tethered float, horizontal plate, and

other types. One of the key characteristics of floating breakwaters is the wave transmission coefficient K_t , which quantifies their ability to reduce the transmissibility of incident waves. This coefficient is defined as follows:

$$K_t = \frac{a_t}{a_i} = \frac{H_t}{H_i} \quad (1)$$

where a_i is the incident wave amplitude, a_t denotes the transmitted wave amplitude, H_i indicates the incident wave height, and H_t corresponds to the transmitted wave height.

K_t is strongly dependent on the incident wave period T , a relationship frequently observed in various studies. Furthermore, rather than T , the ratio B/λ is commonly used, where B represents the breakwater width aligned with the wavelength, typically oriented along the incidence direction of the most recurrent waves, and λ indicates the incident wavelength. A widely recognized result from linear wave theory is provided by Macagno (1953), who derived the theoretical 2D wave transmission coefficient for a rectangular breakwater. Equation (2) presents this analytical formula, developed under the assumptions that the breakwater remains stationary, no green water overtops it, and the water depth remains constant:

$$K_t = \frac{1}{\sqrt{1 + \left[\frac{\pi B \sinh\left(2\pi \frac{h}{\lambda}\right)}{L \cosh\left(2\pi \frac{(h-D)}{\lambda}\right)} \right]^2}} \quad (2)$$

where D indicates the draft, h refers to the water depth, and λ represents the wavelength.

This study investigates how the 3D wave transmission coefficient varies with incident waves in a box-type floating breakwater, aiming to identify hydrodynamic patterns. To achieve this objective, we establish relationships between the breakwater's geometry, the characteristics of the wave-shelter zone shape $\mathcal{S}$ (such as length and beam), and the corresponding K_t values.

Mei and Black (1969) investigated the scattering of surface waves by 2D rectangular objects using a variational formulation for numerical computations. Their study considered surface (semi-immersed) and bottom obstacles with varying proportions. For bottom obstacles, their results aligned with Newman (1965), revealing oscillatory reflection coefficients caused by obstacle-end interactions, with oscillations intensifying as the obstacle length increased. Similarly, surface obstacle results corresponded well with Stoker's approximation (1957), whereas the limiting case of zero-thickness barriers yielded a reflection coefficient of 1. Drimer et al. (1992) developed a simplified analytical model for box-type floating breakwaters in finite-depth waters. This model considered the sway, heave, and roll

motions of the breakwater, regarding the fluid as inviscid, irrotational, and periodic. The sway and heave motions were in good agreement with the fully linearized problem, whereas the roll motion exhibited a tolerable error. They also examined the effect of mooring systems on transmission coefficients, highlighting the effectiveness of a compliant mooring system for large structures.

Elchahal et al. (2009) conducted a parametric study on moored floating rectangular breakwaters, considering the presence of a quay wall. Their analysis revealed challenges associated with resonance bands caused by the quay wall and highlighted the significant influence of various design parameters on system dynamics.

Diamantoulaki and Angelides (2010) numerically investigated the performance of an array of box-type floating breakwaters connected by hinge joints under monochromatic waves. Their findings emphasized the importance of array configuration and wave heading in determining the system's response and effectiveness. Concerning floating box-type breakwaters connected with flexible connectors, Loukogeorgaki et al. (2014) conducted experimental studies on moored arrays. They explored different combinations of wave conditions, revealing the presence of snap loads in some cases and highlighting the impact of wave obliquity on system performance.

In the context of regular waves, the wave transmission coefficient for 2D floating breakwaters is well-established in the literature ((Drimer et al., 1992); (Dong et al., 2008); (Liang et al., 2022)). However, a standardized method for computing the wave transmission coefficient for 3D floating breakwaters remains unavailable.

Different from previous studies focusing on the 2D wave transmission coefficient, the present research investigates the 3D- K_t , which lacks a standardized computational method. To address this gap, the study employs numerical models based on potential flow theory, specifically the Hydrostar Software, to compute K_t for box-type floating breakwaters. Section 2 outlines the problem formulation and methodology, detailing the numerical models used to simulate floating breakwaters under wave action. Similar to previous studies, the attenuation mechanism is *reflection*-based, and the breakwater follows a *box-type* configuration, which has been extensively investigated (Dai et al., 2018). Section 3 presents the hydrodynamic results, analyzing how K_t varies with different geometric and wave conditions. Section 4 demonstrates how machine learning techniques can be applied to predict the sheltered area and optimize breakwater dimensions. Finally, Section 5 summarizes the key findings and their practical implications.

2 Problem formulation and methods

This section aims to define the problem, the proposed

methodology, and other methods used in this work.

2.1 Problem definition and proposed methodology

The problem consists of a generic floating structure (FS) that requires protection from incident wave forces. To achieve this objective, a floating breakwater (FB) is employed, creating a sheltered area that encompasses the FS (Figure 1). The mesh geometry corresponds to a rectangular breakwater, with a panel size approximately one-tenth of the smallest wavelength, sufficiently ensuring numerical convergence (Costa et al., 2023). The breakwater is assumed as a solid body, indicating the absence of sponge layers, flexible parts, and similar modifications. Moreover, lateral walls are excluded as the focus remains on capturing 3D effects.

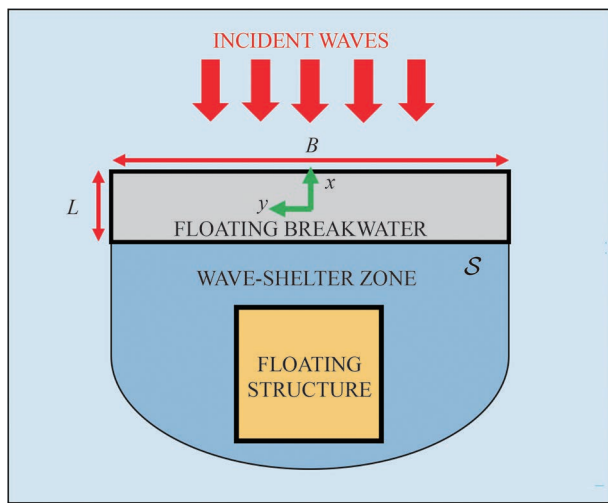


Figure 1 Sheltered area generated by the presence of the floating breakwater (FB) and parameters considered for the FB-FS problem

For FS protection, an FB with length L , breadth B , and draught T , is considered. The incident wave has a length λ , the water depth is h , and the sheltered area of interest, represented by shape $\mathcal{S}$, encompasses FS (Figure 1).

For FB design, the set $\mathcal{P}$ containing all parameters p_i of the problem and the set $\mathcal{B}$ encompassing all associated boundaries b_i related to the previous set, i.e. $\{b_i^- \leq p_i \leq b_i^+ \mid p_i \in \mathcal{P} \text{ and } b_i^+ \in \mathcal{B}^+ \text{ and } b_i^- \in \mathcal{B}^- \text{ and } \mathcal{B}^- \subset \mathcal{B} \text{ and } \mathcal{B}^+ \subset \mathcal{B}\}$ are defined (Figure 2). The design methodology is described in the next subsection.

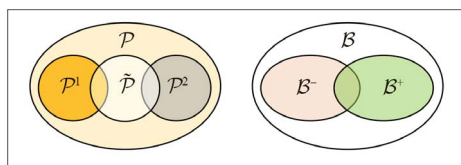


Figure 2 Set $\mathcal{P}$ that contains all parameters p_i of the problem (left) and set $\mathcal{B}$ that contains all boundaries b_i of the problem (right)

2.1.1 Design methodology

When considering regular waves, the wave transmission coefficient for 2D FBs is well-defined in the literature ((Drimer et al., 1992); (Dong et al., 2008); (Liang et al., 2022)). However, a standardized computational method for determining the wave transmission coefficient of 3D floating breakwaters remains undeveloped. FB motion caused by waves generates *radiated* waves that overlap with transmitted waves in the sheltered area (Guo et al., 2022). As a result, a tight mooring system is generally advantageous for wave attenuation (Loukogeorgaki and Angelides, 2005), as it restricts FB movement, thereby minimizing radiated waves. In this study, we consider a tightly taut mooring system to limit FB motion, resulting in negligible radiated waves. We begin by identifying the hydrodynamics patterns related to the diffraction problem and examining their influence on the wave transmission coefficient K_t . These insights contribute to the computational methodology for K_t in the 3D floating breakwater problem. Given that this study focuses exclusively on the diffraction problem, these patterns depend solely on the breakwater geometry (Dimensional analysis in Appendix A), represented by the subset $\mathcal{P}^1 \subset \mathcal{P}$. Thus, we analyze the relationship between the breakwater geometry, the characteristics of the wave-shelter zone shape $\mathcal{S}$, and the K_t values. Other aspects, such as wave-induced forces and hydrodynamic coefficients, are beyond the scope of this study; a thorough discussion on these topics can be found in Mohapatra et al. (2024).

The design methodology considers the variable set $\mathcal{P}^1 = \{L, B, T, \lambda, h\}$ and follows these step-by-step procedures:

1. The boundary values related to $\mathcal{P}^1$ are defined.
2. Given that diffraction is negligible for high values of wavelength λ (compared to the breakwater length L), we evaluate different values of λ to determine their impact on diffraction.
3. For all previously defined cases, sheltered areas with shape $\mathcal{S}$ for different values of K_t are mapped.
4. Finally, we analyze the relationships among $\mathcal{P}^1$, the corresponding sheltered area shape $\mathcal{S}$, and the K_t values by plotting the results that include $\mathcal{P}^1$, $\mathcal{S}$, and K_t .

The wave-shelter zone (WSZ) of interest may exhibit varying shapes. In addition, as K_t values vary within this WSZ, we compute their mean μ_{K_t} and standard deviation σ_{K_t} , as defined in Equation (1).

In all cases considered in this study, the incident wave has a unit amplitude, leading to the following equation:

$$K_t = \frac{a_t}{a_i} \Rightarrow K_t = \frac{a_t}{1} \Rightarrow K_t = a_t \quad (3)$$

where the transmitted wave amplitude a_t is defined as the magnitude of the total complex amplitude. This amplitude varies based on the x and y within the domain, expressed

as: $a_t = |a_{\text{total}}(x, y)|$.

Following the discussion of the obtained results, we demonstrate a practical approach to designing FBs for off-shore structure protection. In our example case, an FB is optimized to protect a 1-megawatt floating solar photovoltaic (FPV) structure from ocean waves. The sheltered area is predicted using machine learning models applied to previously gathered data, specifically focusing on the sheltered length ($\mathcal{S}_{L_{\text{POS}}}$) and beam ($\mathcal{S}_{B_{\text{POS}}}$) required by the protected offshore structure (POS), as well as the necessary wave transmission coefficient $K_{t_{\text{POS}}}$. A gradient boosting regressor (GBR) model was identified as the most accurate predictor, and optimization was conducted using the differential evolution (DE) method to minimize construction costs while ensuring adequate wave protection. The final breakwater dimensions are determined based on the outlined constraints.

2.2 Background theory

The variables of interest have been defined in the previous section. This section presents the background theory, focusing specifically on the hydrodynamic principles relevant to the problem.

2.2.1 Hydrodynamics of a floating body

A 3D floating body subject to small-amplitude plane progressive waves with sinusoidal time dependence and a direction of θ is considered (Figure 3). Given that the wave amplitude A is sufficiently small to justify linearization, linear potential flow is assumed.

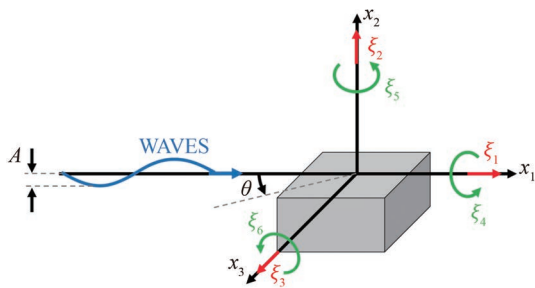


Figure 3 Floating body with six degrees of freedom (ξ_1 , ξ_2 , ξ_3 , ξ_4 , ξ_5 , and ξ_6 representing surge, heave, sway, roll, yaw, and pitch, respectively) and an incident wave of amplitude A and direction θ

The equation of motion for a floating body in waves was derived by Newman (2017), with a summary of this derivation shown here. Assuming an incompressible, inviscid, and irrotational flow, the potential function $\phi(x, y, z, t)$ is defined to satisfy the conservation of mass and momentum. The velocity vector $\mathbf{V}$ is then expressed as the gradient of the velocity potential function, as follows:

$$\mathbf{V} = \nabla \phi \quad (4)$$

Considering a stable floating body with the following six degrees of freedom: surge (ξ_1), heave (ξ_2), sway (ξ_3), roll (ξ_4), yaw (ξ_5), and pitch (ξ_6), subject to a small amplitude incident wave, the velocity potential function can be written as follows:

$$\phi = \phi_R + \phi_D \quad (5)$$

where the potential ϕ_R is attributed to the oscillation of the body in the absence of the incident waves, and the potential ϕ_D is induced by the incident waves and their interaction with the body. Thus, using the complex amplitude notation, we obtained the following:

$$\phi(x, y, z, t) = \text{Re} \left\{ \phi(x, y, z) e^{i\omega t} \right\} \quad (6)$$

where t indicates time, and ω denotes the same frequency as the incident waves. Equation (6) can be expanded as follows:

$$\phi(x, y, z, t) = \text{Re} \left\{ \left(\sum_{j=1}^6 \xi_j \phi_j(x, y, z) + A \phi_A(x, y, z) \right) e^{i\omega t} \right\} \quad (7)$$

which is the decomposition of the total potential into the terms given by Equation (5), where ϕ_j represents the velocity potential of a rigid-body motion in the j th mode with unit amplitude, in the absence of the incident waves, and $\phi_A = \phi_D/A$ indicates the potential due to the incident wave and its interaction with the body, assuming the body is stationary.

Concerning the boundary conditions on the body surface S_B , the potentials we impose are expressed as follows:

$$\frac{\partial \phi_j}{\partial n} = i\omega n_j, \quad j = 1, 2, 3 \quad (8)$$

$$\frac{\partial \phi_j}{\partial n} = i\omega (\mathbf{r} \times \mathbf{n})_{j-3}, \quad j = 4, 5, 6 \quad (9)$$

$$\frac{\partial \phi_A}{\partial n} = 0, \quad \text{on } S_B \quad (10)$$

where $\partial/\partial n$ denotes the derivative in the direction of $\mathbf{n}$ directed out of the fluid, $\mathbf{n}$ indicates the unit normal vector on the body surface (directed into the body), and $\mathbf{r}$ corresponds to the position vector. Equations (8) and (9) equate the normal derivative of each ϕ_j to the normal component of the body velocity, whereas Equation (10) sets the normal derivative of ϕ_A to zero, given that the body is assumed to be fixed in position.

The potentials ϕ_j (which are part of ϕ_R) represent solutions to the radiation problem, while the potential ϕ_A (which is part of ϕ_D) corresponds to the solution of the diffraction problem. The latter can ultimately be decomposed into two

components, as follows:

$$\phi_A = \phi_0 + \phi_7 \quad (11)$$

where ϕ_0 denotes the incident wave potential, and ϕ_7 indicates the potential caused by the disturbance to the incident wave potential associated with the scattering effect of the body.

Furthermore, all potentials must satisfy the Laplace equation throughout the domain of the fluid, as follows:

$$\nabla^2 \phi_j = 0, \quad j = 0, 1, \dots, 6, 7 \quad (12)$$

The condition on the bottom, for a finite depth h , is satisfied as follows:

$$\frac{\partial \phi_j}{\partial y} = 0, \quad y = -h, \quad j = 0, 1, \dots, 6, 7 \quad (13)$$

or that for an infinite depth, as follows:

$$\phi_j \rightarrow 0 \text{ as } y \rightarrow -\infty, \quad j = 0, 1, \dots, 6, 7 \quad (14)$$

On the free surface, the linearized kinematic–dynamic boundary condition is expressed as follows:

$$-\frac{\omega^2}{g} \phi_j + \frac{\partial \phi_j}{\partial y} = 0, \text{ on } y = 0, \quad j = 0, 1, \dots, 6, 7 \quad (15)$$

where g represents the gravitational acceleration. To achieve unique solutions, excluding the incident wave potential ϕ_0 , the other ones must satisfy the radiation condition, which states that waves associated with the potentials ϕ_j , $j = 1, \dots, 7$ must be radiating away from the body, thus:

$$\phi_j \propto R^{-1/2} e^{-ikR}, \text{ as } R \rightarrow \infty, \quad j = 1, \dots, 6, 7 \quad (16)$$

where $R = \sqrt{x^2 + z^2}$, and k indicates the wavenumber (defined as $k = 2\pi/\lambda$, where λ denotes the wavelength).

Finally, the forces $\mathbf{F}$ and moments $\mathbf{M}$ on the body can be obtained through the integration of the pressure over S_B as follows:

$$\mathbf{F} = \iint_{S_B} p \mathbf{n} dS \quad (17)$$

$$\mathbf{M} = \iint_{S_B} p (\mathbf{r} \times \mathbf{n}) dS \quad (18)$$

where p indicates pressure:

$$p = -\rho \left(\frac{\partial \phi}{\partial t} + gy \right) = -\rho \operatorname{Re} \left\{ \left(\sum_{j=1}^6 \zeta_j \phi_j + A(\phi_0 + \phi_7) \right) i\omega e^{i\omega t} \right\} - \rho gy \quad (19)$$

Substituting Equation (19) in (17) and (18) obtains the following:

$$\begin{pmatrix} \mathbf{F} \\ \mathbf{M} \end{pmatrix} = -\rho g \iint_{S_B} \begin{pmatrix} \mathbf{n} \\ \mathbf{r} \times \mathbf{n} \end{pmatrix} y dS - \rho \operatorname{Re} \sum_{j=1}^6 i\omega \zeta_j e^{i\omega t} \iint_{S_B} \begin{pmatrix} \mathbf{n} \\ \mathbf{r} \times \mathbf{n} \end{pmatrix} \phi_j dS - \rho \operatorname{Re} i\omega A e^{i\omega t} \iint_{S_B} \begin{pmatrix} \mathbf{n} \\ \mathbf{r} \times \mathbf{n} \end{pmatrix} (\phi_0 + \phi_7) dS \quad (20)$$

where the first term on the RHS denotes the hydrostatic component, the second one resembles the damping and added-mass coefficients, and the last one indicates the exciting force or moment, which is proportional to the incident wave amplitude. Defining $\mathbf{F} = F_i$, $i = 1, 2, 3$, and $\mathbf{M} = F_i$, $i = 4, 5, 6$, and developing each of these terms, we obtain the following:

$$F_i = -\sum_{j=1}^6 c_{ij} \zeta_j + \operatorname{Re} \left\{ \sum_{j=1}^6 \zeta_j e^{i\omega t} (\omega^2 a_{ij} - i\omega b_{ij}) \right\} + \operatorname{Re} \{ A e^{i\omega t} X_i \}, \quad i = 1, 2, \dots, 6 \quad (21)$$

where the terms of the matrix c_{ij} are defined as follows:

$$\begin{aligned} c_{22} &= \rho g S, \\ c_{44} &= \rho g S_{33} + \rho g \forall y_B - mgy_G, \\ c_{45} &= -g(\rho \forall x_B - mx_G), \\ c_{65} &= -g(\rho \forall z_B - mz_G), \\ c_{66} &= \rho g S_{11} + \rho g \forall y_B - mgy_G \end{aligned} \quad (22)$$

where S indicates the waterplane area, (x_B, y_B, z_B) represent the positions of the center of buoyancy, (x_G, y_G, z_G) denote the positions of the center of gravity, $\forall$ refers to the displaced volume, the waterplane moments $S_{ij} = \iint_{S_0} x_i x_j dS$

with S_0 denote the waterplane in the static condition, a_{ij} indicates the matrix of added-mass coefficients, b_{ij} is the matrix of damping coefficients, and X_i represents the complex amplitude of the exciting force or moment, in the direction i , for an incident wave of unit amplitude. Considering the inertial force $F_i = -\omega^2 \sum_{j=1}^6 M_{ij} \zeta_j$, $i = 1, 2, \dots, 6$, we

have the following:

$$-\omega^2 \sum_{j=1}^6 M_{ij} \zeta_j = \sum_{j=1}^6 \zeta_j \left(-c_{ij} + (\omega^2 a_{ij} - i\omega b_{ij}) \right) + A X_i, \quad i = 1, 2, \dots, 6 \quad (23)$$

where M_{ij} is defined as follows:

$$M_{ij} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & -my_G \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & my_G & 0 & 0 \\ 0 & 0 & my_G & I_{11} & I_{12} & I_{13} \\ 0 & 0 & 0 & I_{21} & I_{22} & I_{23} \\ -my_G & 0 & 0 & I_{31} & I_{32} & I_{33} \end{bmatrix} \quad (24)$$

where m is the body mass, and I_{ij} represents the moments of inertia. Finally, rearranging Equation (23), we obtain the equation of motion, as follows:

$$\sum_{j=1}^6 \zeta_j \left[-\omega^2 (M_{ij} + a_{ij}) + i\omega b_{ij} + c_{ij} \right] = AX_i, \quad i = 1, 2, \dots, 6 \quad (25)$$

Given the assumption of linear potential flow, the radiation/diffraction approach requires a panelized submerged geometry to calculate the velocity potential field and enforce boundary conditions. To capture convergence using mesh refinement, a panel size approximately one-tenth of the smallest wavelength is sufficient (Costa et al., 2019; Costa et al., 2023).

2.2.2 Numerical approach

This study uses Hydrostar Software, a 3D diffraction/radiation tool developed by Bureau Veritas (2024) based on potential theory for wave-body interactions. Similar to other software, such as WAMIT (WAMIT, 1999), NEMOH (Kurnia and Ducrozet, 2023), and Capytaine (Ancellin and Dias, 2019), Hydrostar models the fluid as an ideal medium, assuming it is inviscid and incompressible, while treating the flow as irrotational. As described in the previous section, this approach enables fluid motion to be represented through a velocity potential. Thus, the interaction between waves and bodies can be formulated and solved numerically.

This approach relies on boundary integral equations, solved using a boundary element method. Instead of solving the governing equations throughout the entire fluid domain, the problem is reduced to computing an integral equation on the domain boundary. It includes the surface of the floating body and the free water surface.

To apply this method, the submerged surface of the body must be discretized into a mesh of flat quadrilateral or triangular panels (Figure 4). Thus, on each panel, a distribution of singularities, typically sources or dipoles, is assumed. Finally, the strengths of these singularities are determined by satisfying the boundary conditions on the body (e.g., no flow through the hull for a fixed body, or prescribed motion for radiation problems) and on the free surface (dynamic and kinematic conditions).

2.3 Differential evolution

The classical DE is used for single-objective problems proposed by Storn and Price (1997). Moreover, the Python implementation of this method, namely pymooDE, found

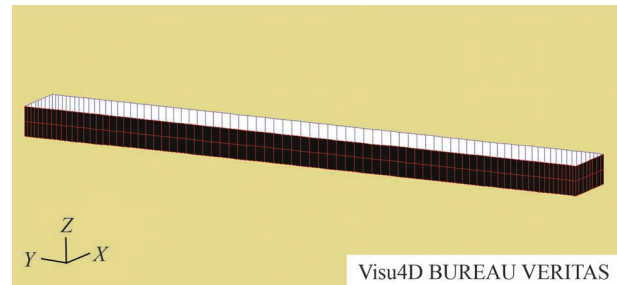


Figure 4 Example of a panelized rectangular body opened at the visu4D from bureau veritas (2024)

in the literature (Leite, Costa, and Costa Junior, 2023), is supported by the Python multi-objective optimization package known as pymoo (Blank and Deb, 2020).

The DE variant used for the present work is **DE/rand/1/bin**, with each term defined as follows:

- **DE**: differential evolution method;
- **rand**: a randomly chosen population vector;
- **1**: number of difference vectors used;
- **bin**: crossover due to independent binomial experiments.

The pseudocode for this classical DE is based on the work of Reddy and Kumar (2007), as shown in Algorithm 1. The best individual from the population is based on the objective function value.

Algorithm 1 Pseudocode of the DE variant **DE/rand/1/bin** (Reddy and Kumar, 2007)

```

Generate initial population of size NP
while the termination condition is not satisfied do
    for each individual  $j$  in the population do
        Generate three random integers  $r_1, r_2, r_3 \in (1, NP)$ , with
         $r_1 \neq r_2 \neq r_3 \neq j$ 
        Generate a random integer  $i_{\text{rand}} \in (1, n)$ 
        for each parameter  $i$  do
             $x_{i,j} = \begin{cases} x_{i,r_3} + F * (x_{i,r_1} - x_{i,r_2}), & \text{if } \text{rand}(0, 1) < CR \text{ or } i = i_{\text{rand}} \\ x_{i,j}, & \text{otherwise} \end{cases}$ 
        end for
        If  $x'_j$  is better then replace  $x_j$  with the child  $x'_j$ 
    end for
end while

```

3 Results and discussion

This section presents the results related to the variation of the 3D wave transmission coefficient due to incident waves, specifically examining hydrodynamics patterns related to the diffraction problem. We analyze the association between breakwater geometry, WSZ shape $\mathcal{S}$, and K_p . For this study, the following parameter values were adopted: $L = \{100, 500\}$ m, $B = \{5, 25\}$ m, $T = \{5, 25\}$ m, $\lambda = \{25, 75, 150, 300, 600\}$ m, and $h = \{30, 100\}$ m. In all cases, the domain measures 3 000 m in length and 700 m in

width, with an incident wave of unit amplitude.

3.1 Different K_t levels emerge for the same case

To obtain the WSZ shape $\mathcal{S}$ behind the breakwater, we created a contour of the area containing values less than or equal to a given $K_{t_{\max}}$ (Figure 5). The shape $\mathcal{S}$ varied significantly with variations in breakwater length L , breadth B , draught T , wavelength λ , and $K_{t_{\max}}$ (Figure 6). However, the results show negligible variations for different values of water depth h . In terms of WSZ shape $\mathcal{S}$, breakwaters with small B/λ ratios exhibited a tooth-like shape with the point close to the breakwater and the cleft backward, whereas higher B/λ ratios lead to Christmas-tree-like shapes with the base close to the breakwater and the top backward. The recommended placement for a floating offshore structure is generally near the breakwater. However, depending on K_t , in some cases, the WSZ is relatively far from the breakwater, such as when $T = 5$ m, $L = 25$ m, $B = 500$ m, $\lambda = 150$ m, and $K_{t_{\max}} = 0.1$ in Figure 6. The results indicate that, differently from 2D scenarios (with only one K_t value), multiple K_t levels emerge in 3D cases. For a given $K_{t_{\max}}$, the K_t variation within the WSZ results from destructive and constructive interferences of the scattered wave. Furthermore, in practice, the waterplane of floating offshore structures more closely resembles regular shapes than the tooth-like or Christmas-tree-like formations observed in WSZs. This discrepancy complicates the integration of such structures into the WSZ.

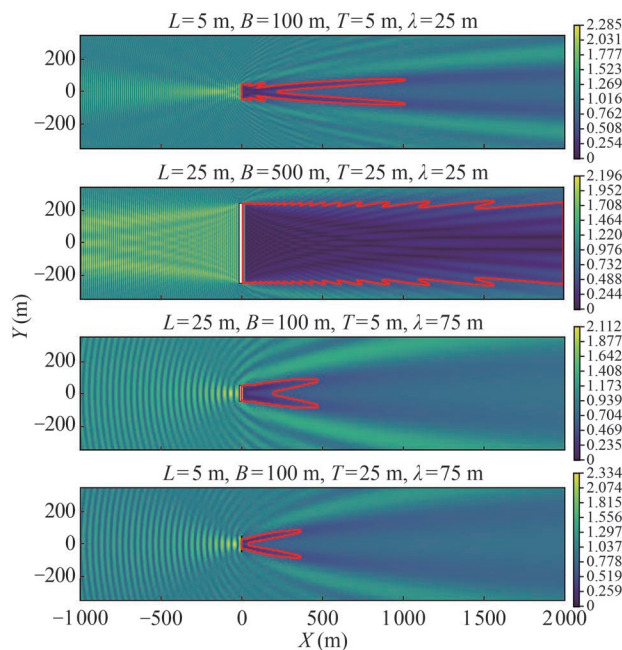


Figure 5 Wave elevation for breakwaters with different values of L , B , T , and λ . The red contour indicates the irregular wave-shelter zone shape for $K_{t_{\max}} = 0.5$

3.2 Higher B/λ ratios have convergent mean K_t levels

To observe how K_t varies with different relative breakwater beam ratios (B/λ), we analyzed multiple cases, identifying the corresponding WSZs and computing the mean wave transmission coefficient μ_{K_t} and its standard deviation σ_{K_t} within these regions. For small relative breakwater beam ratios, i.e., B/λ up to 2, the μ_{K_t} values were spaced approximately 0.1. Conversely, higher (B/λ) ratios exhibited a decreasing trend in this spacing along with an overall reduction in μ_{K_t} values (Figure 7). In addition, as expected, the results for wider breakwaters ($B = 500$ m) closely align with the 2D analytical solution proposed by Macagno (1953) (dashed red curves in Figure 7), which demonstrates a significant decline in μ_{K_t} as the B/λ ratio increases. These findings suggest that higher relative breakwater beam ratios (B/λ) lead to convergent μ_{K_t} values. Appendix B provides a comprehensive list of μ_{K_t} and σ_{K_t} values for all cases.

Considering the relative breakwater beam ratios (B/λ) and the achieved K_t levels, 2D breakwaters studied by Macagno (1953) demonstrate greater effectiveness than 3D breakwaters at high B/λ ratios (~ 20). Conversely, at very low B/λ ratios (~ 1), the 3D breakwaters outperform their 2D counterparts. Intermediate cases appear to be influenced by geometric characteristics, such as length, breadth, and draught. For example, in the case where $L = 25$ m, $B = 500$ m, and $T = 5$ m: at $B/\lambda = 20$, the minimum 2D- K_t achieved is approximately 0.07, whereas the 3D- K_t is approximately 0.14. This finding indicates a 50% improvement in effectiveness when transitioning from 3D to 2D. At $B/\lambda = 2$, the minimum 2D- K_t achieved is approximately 0.95, whereas the 3D- K_t is approximately 0.44. In this case, shifting from 2D to 3D yields a 54% improvement in effectiveness.

3.3 Wave-shelter area is strongly dependent on the relative breakwater beam ratio

To analyze changes in the wave-shelter area across different cases, rectangles were fitted within the contours corresponding to various K_t levels (Figure 8). This adjustment was performed using the DE, which determined the area of a rectangular wave-shelter zone $\mathcal{S}_A$, with breadth $\mathcal{S}_B$ and length $\mathcal{S}_L$. To introduce a nondimensional parameter, we computed the relative sheltered area ratio ($\mathcal{S}_A/\mathcal{S}_{RA}$), where $\mathcal{S}_{RA}$ represents the available area behind the breakwater, i.e., limited by the breakwater breadth B and a rear domain of 2000 m. For small relative breakwater beam ratios (B/λ), the relative sheltered area ratios ($\mathcal{S}_A/\mathcal{S}_{RA}$) exhibited low values. Conversely, higher values of B/λ increase the value of $\mathcal{S}_A/\mathcal{S}_{RA}$. For wider breakwaters, additional K_t levels emerge, generating more protected zones (Figure 9). These find-

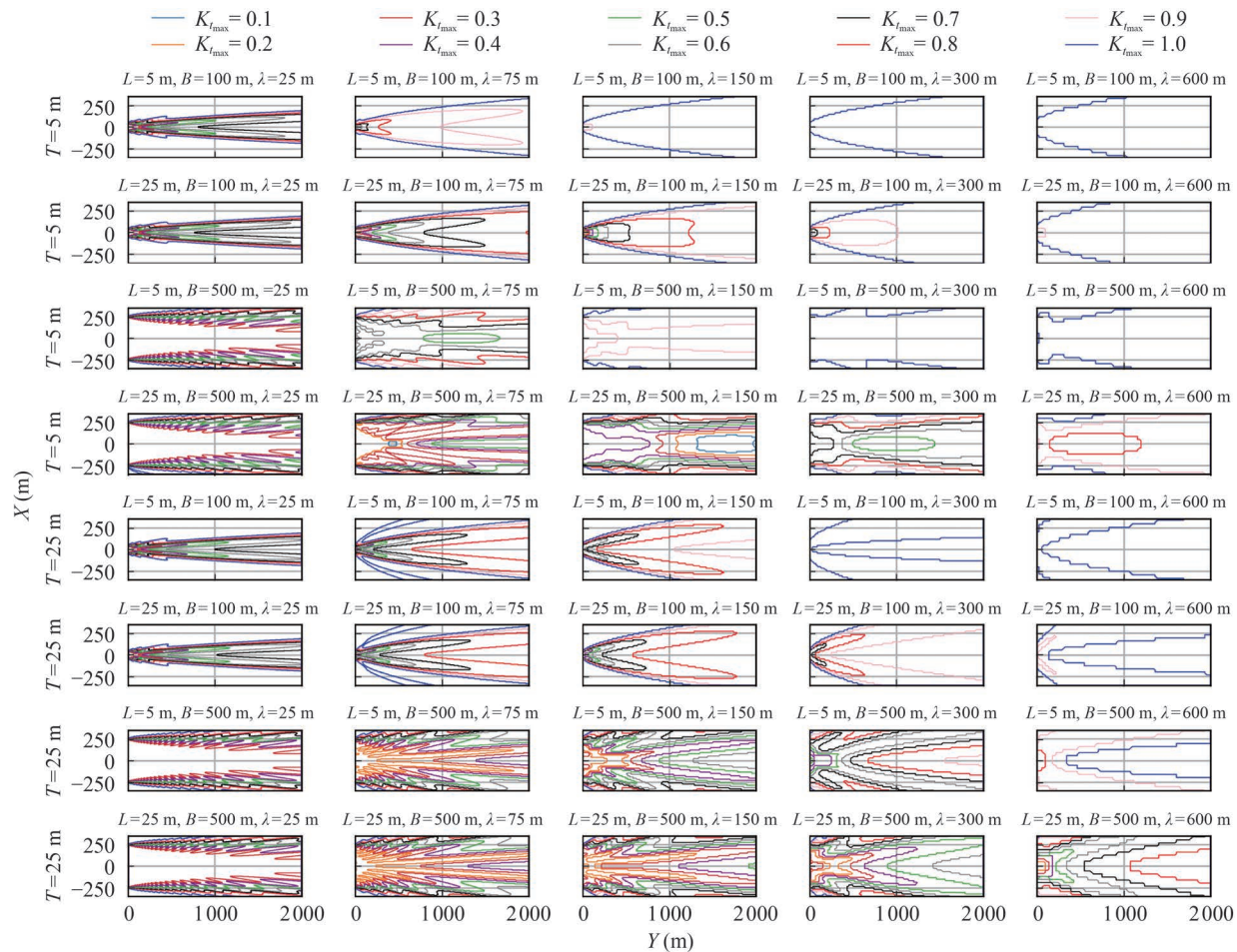


Figure 6 Wave-shelter zone contours for different values of L , B , T , λ , and K_t

ings highlight the strong dependence of wave-shelter area on the breakwater beam ratio (B/λ). In addition, lower K_t levels can be achieved by increasing the ratios B/λ , B/L , and B/T . Furthermore, the rectangular sheltered area exhibits an exponential relationship with K_t levels (Figure 10), suggesting that floating offshore structures requiring protection are best suited to occupying a relatively small area.

4 Designing an extremely large floating breakwater for a floating solar photovoltaic system protection

In designing the FB, we consider a scenario where the POS is a 1 megawatt-peak (MWp) floating solar photovoltaic (FPV) system. Standard solar panels measuring 2.4 m in height and 1.3 m in width, each capable of producing approximately 600 watt-peak (Wp), result in 1 680 units forming a square area of approximately 72 m per side. To maintain a conservative approach, the design adopts a square footprint of 100 m per side, defining $\mathcal{S}_{L_{POS}} = \mathcal{S}_{B_{POS}} = 100$ meters. The selected wave transmission coefficient

is $K_{t_{POS}} = 0.5$, ensuring a 50% reduction in incident wave amplitude.

To establish relationships among the breakwater, the rectangular WSZ shape $\mathcal{S}$, and the wave transmission coefficient K_t , we used different regression machine learning (ML) algorithms from the Scikit-Learn package (Pedregosa et al., 2012). These regression techniques include linear regression (LR), polynomial regression (PR), decision tree regressor (DTR), gradient boosting regressor (GBR), random forest regressor (RFR), and multi-layer perceptron (MLP), which are commonly applied in regression-based prediction studies (Ferreira et al., 2022). These methodologies encompass least-squares approaches, tree-based learners, and neural network-based approaches, which are briefly described below:

- Least-squares techniques:

- Linear Regression represents one of the simplest and most interpretable prediction methods, assuming a linear relationship between the target and the input features (Kramer, 2016).

- Polynomial Regression extends the previous concept by modeling the relationship between inputs and the target as a polynomial function, thereby capturing nonlinear patterns.

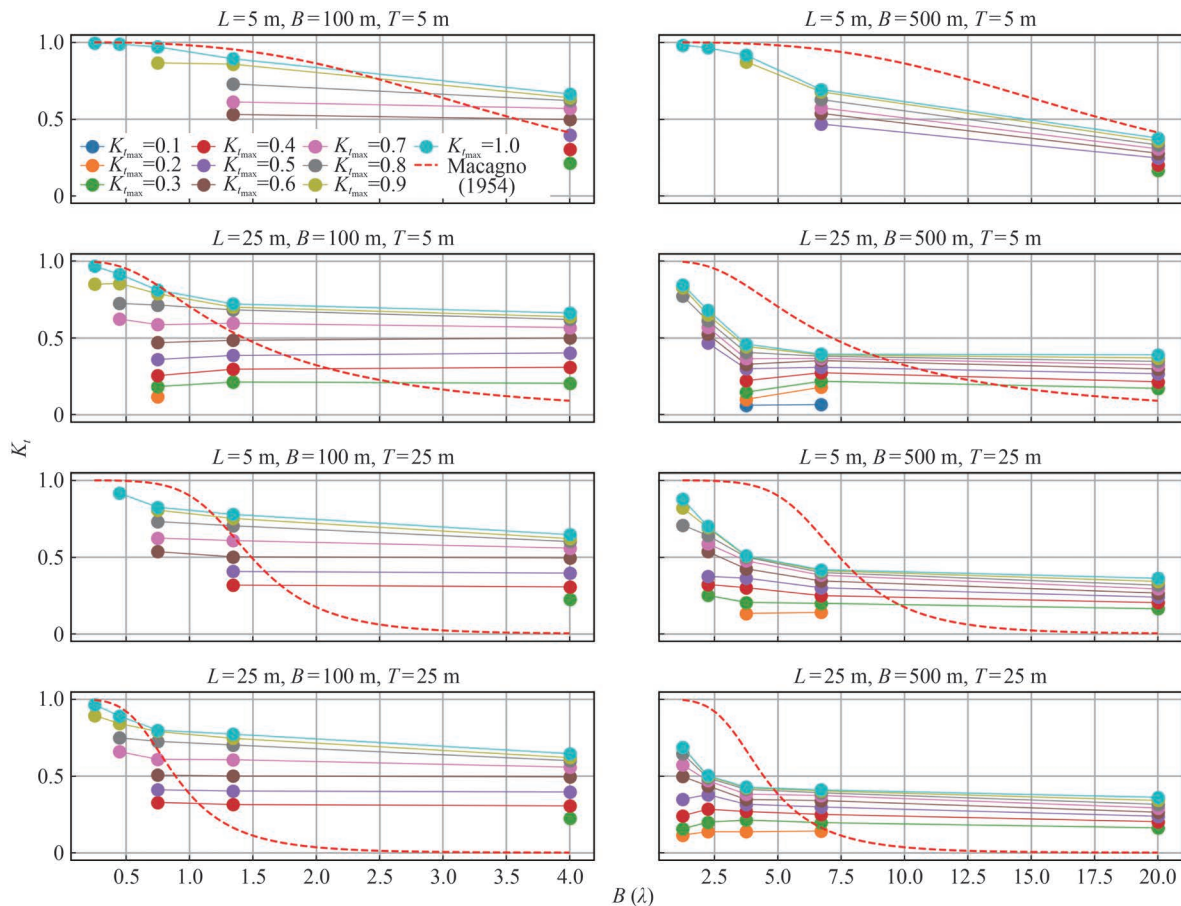


Figure 7 Mean wave transmission coefficient μ_{K_t} for different values of L , B , and T , versus B/λ . The dashed red curves are given by the 2D analytical solution by Macagno (1953)

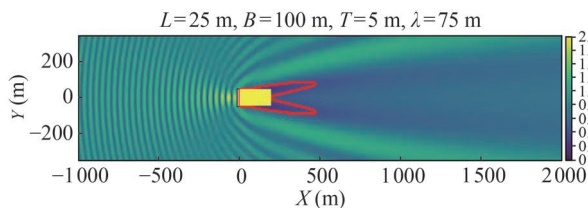


Figure 8 Wave elevation for the case $L = 25$ m, $B = 100$ m, $T = 5$ m, and $\lambda = 75$ m. The red contour indicates the irregular wave-shelter zone shape for $K_{t_{max}} = 0.5$. The yellow rectangle denotes the one adjusted within the red contour

- Decision tree learners:

- Decision Tree Regressor is a nonparametric model that splits data into regions using input feature values and predicts a constant value for each region.

- Gradient Boosting Regressor is an ensemble method that builds a sequence of shallow decision trees, where each new tree attempts to correct the residual errors of the ensemble (Friedman, 2001).

- Random Forest Regressor constructs an ensemble of independent decision trees, each trained on different subsets of data through bootstrap sampling and using random subsets of features (Breiman et al., 2017; Coppersmith

et al., 1999).

- Neural network-based approach:

- Multi-Layer Perceptron Regressor: is a feedforward artificial neural network that captures complex nonlinear relationships between inputs and outputs. In this approach, a backpropagation optimization method is used (Riedmiller and Braun, 1993).

The step-by-step procedure of the pipeline (Figure 11) to predict the sheltered length ($\mathcal{S}_L$) and beam ($\mathcal{S}_B$) is as follows:

- ① Data from the simulations were loaded (Appendix C), and features were separated from the targets.

- ② Data were normalized to a 0–1 range.

- ③ Data are divided into two subsets: (70%) training set and (30%) test set.

- ④ Here, six models were used: LR, PR, DTR, GBR, RFR, and MLP.

- ⑤ Each model's hyperparameters were optimized using a grid search with fivefold cross-validation, minimizing the R -squared (R^2) value.

- ⑥ The models were trained using the optimized parameters.

- ⑦ Models were evaluated on test data using R^2 , mean

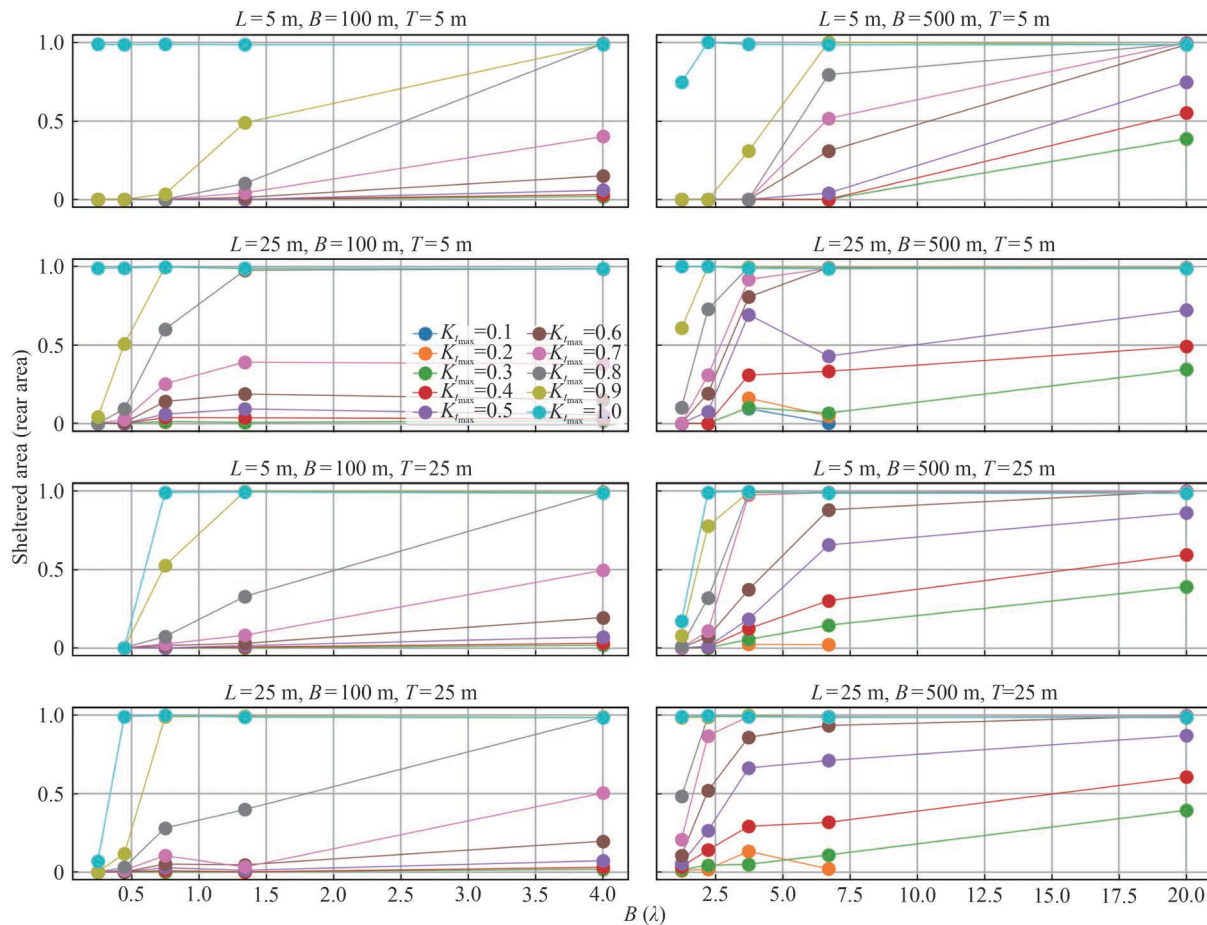


Figure 9 Relative sheltered area ratios ($\mathcal{S}_A/\mathcal{S}_{RA}$) for different relative breakwaters beam ratios (B/λ) and K_t levels. The value of $\mathcal{S}_A$ is derived from the rectangular sheltered area. The value of $\mathcal{S}_{RA}$ is obtained from the breakwater rear area

absolute error (MAE), mean squared error (MSE), and root mean squared error (RMSE) to summarize predictive performance.

The trained models are available at https://github.com/mrsonandrade/rectangular_breakwater. The best-performing models were selected based on their higher R^2 values and lower MAE, MSE, and RMSE scores (Table 1). Among the evaluated algorithms, the GBR was selected to predict the sheltered length ($\mathcal{S}_L$) and beam ($\mathcal{S}_B$), as it consistently demonstrated strong performance for both predictions. Therefore, GBR will be used to optimize the FB dimensions. Given the presented metric values, the model's high R^2 , combined with low RMSE and MAE, suggests a well-balanced accuracy and error performance.

To optimize the FB dimensions, the objective function is defined as follows:

$$f_{obj} = \min \left(\frac{LBT}{\sum_{\lambda, K_t, \zeta}} \right) \quad \therefore \quad (26)$$

$$\zeta = \begin{cases} e^{9(K_{t_{pos}} - K_t)}, & \text{if } \mathcal{S}_L \geq \mathcal{S}_{L_{pos}} \text{ and } \mathcal{S}_B \geq \mathcal{S}_{B_{pos}} \\ 0, & \text{otherwise} \end{cases}$$

Subject to:

$$\begin{aligned} 5 &\leq L \leq 25 \\ 100 &\leq B \leq 500 \\ 5 &\leq T \leq 25 \end{aligned} \quad (27)$$

with $\lambda = \{25, 75, 150, 300, 600\}$ and $K_t = \{0.5, 0.6, 0.7, 0.8, 0.9, 1.0\}$. In Equation (26), LBT denotes the volume of the FB, which is proportional to its building cost; $\sum_{\lambda, K_t} \zeta$ represents all combinations of λ and K_t ; it increases when $\mathcal{S}_{pos}$ values are satisfied and the K_t values are closer to $K_{t_{pos}}$. The optimization uses the DE method considering Equations (26) and (27), with the code available at https://github.com/mrsonandrade/rectangular_breakwater.

To apply the DE method, the mutation factor F , cross-over rate CR, and population size were varied to identify the optimal combinations for the proposed approach. All combinations of the following values were tested: seed = $\{1\}$, $F = \{0.8, 0.9, 1.0\}$, $CR = \{0.2, 0.3, 0.4, 0.7, 0.8, 0.9\}$, and population size = $\{10, 20, 30\}$. The best combinations were those that minimize the objective function value with fewer evaluations and a maximum evaluation count of

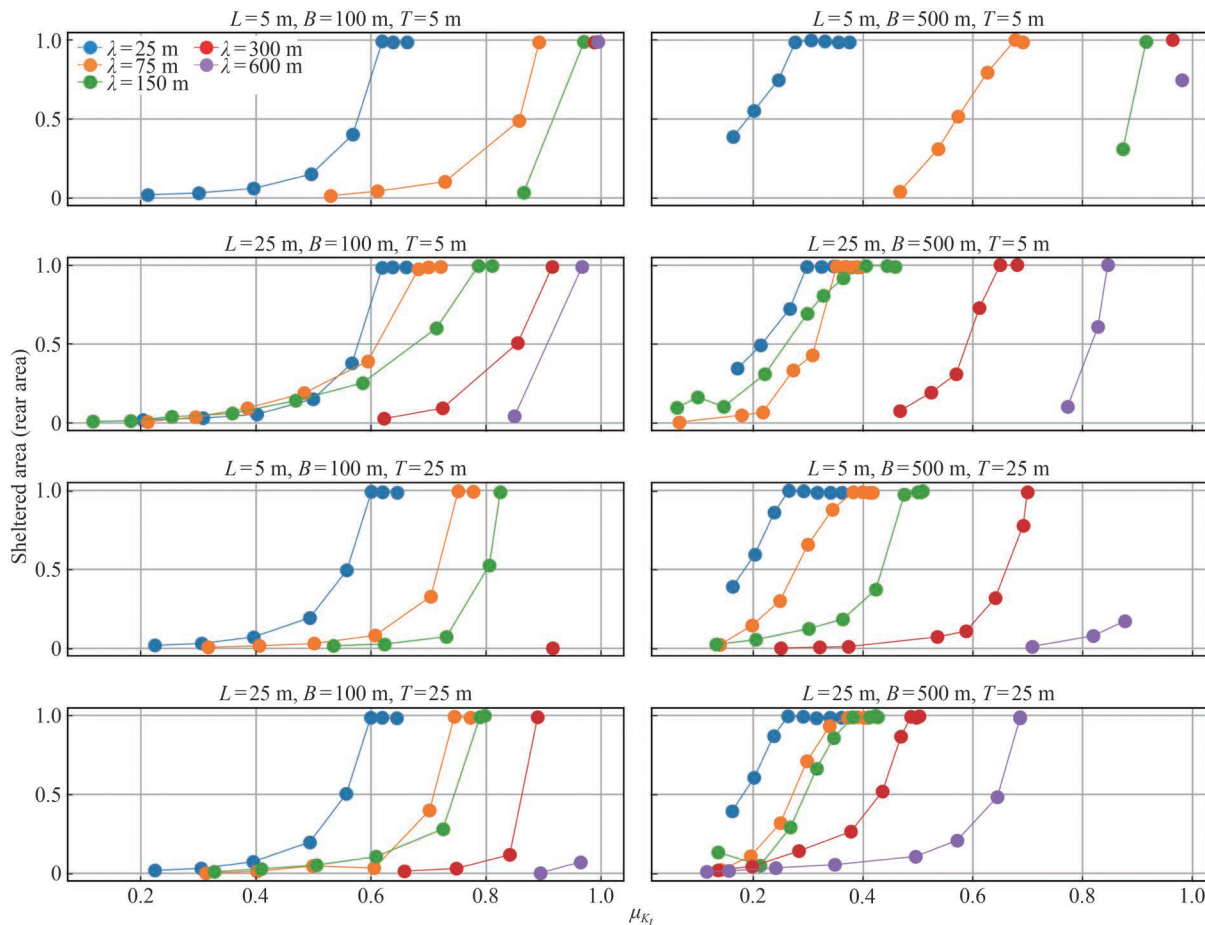


Figure 10 Relative sheltered area ratios (S_A/S_{RA}) for different μ_{K_i} and wavelengths λ

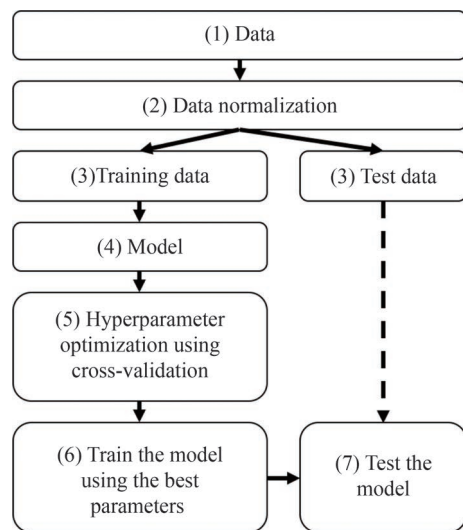


Figure 11 Step-by-step pipeline procedure for predicting sheltered length (S_L) and beam (S_B)

3 000. The final parameter set was determined considering the mode, i.e., the most frequent values among the best combinations, that is, $F = 0.8$, $CR = 0.7$, and a population

Table 1 R^2 , MAE, MSE, and RMSE for each model trained using ML models. These values were obtained using the Test set

Model	S_L prediction				S_B prediction			
	R^2	MAE	MSE	RMSE	R^2	MAE	MSE	RMSE
LR	0.52	0.25	0.08	0.29	0.76	0.13	0.03	0.18
PR	0.64	0.20	0.06	0.25	0.84	0.09	0.02	0.14
DTR	0.56	0.14	0.08	0.28	0.73	0.10	0.03	0.19
GBR	0.75	0.14	0.04	0.21	0.84	0.09	0.02	0.14
RFR	0.61	0.16	0.07	0.26	0.83	0.08	0.02	0.15
MLP	0.70	0.14	0.05	0.23	0.84	0.09	0.02	0.14

size of 10. Figure 12 and Table 2 illustrate the results from this parameter adjustment stage.

FB can be optimized following parameter adjustment using the DE method for seed = $\{1, \dots, 30\}$, $F = 0.8$, $CR = 0.7$, and a population size of 10. Given that all optimal configurations achieved the minimum fitness value within 250 evaluations (Table 2), the maximum number of evaluations was set to 1 000. Figure 13 and Table 3 demonstrate the results of the breakwater optimization.

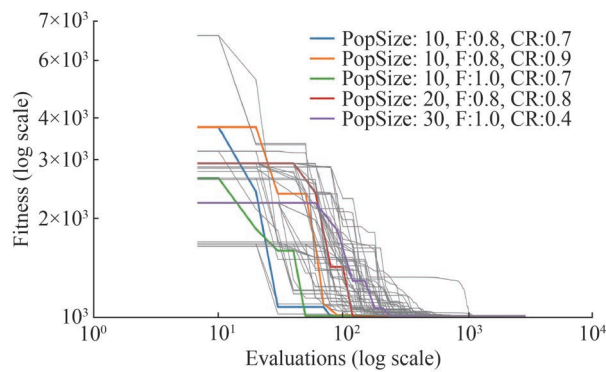


Figure 12 DE parameter adjustment to find the best combinations. Fitness evolution for all tested cases. The five (colored) combinations are those that achieved lower fitness values in fewer evaluations

Table 2 Five best results for the parameter adjustment stage of DE

Case	Evals	Best fitness	Population size	F	CR
A	120	990.320	20	0.8	0.8
B	230	990.872	10	1.0	0.7
C	240	990.505	30	1.0	0.4
D	250	990.431	10	0.8	0.7
E	250	990.733	10	0.8	0.9

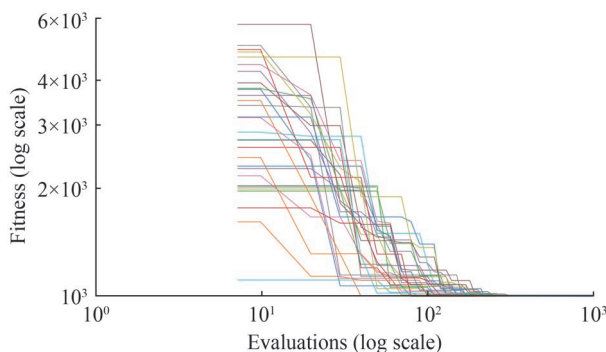


Figure 13 Fitness evolution for the floating breakwater optimization to find the best combinations. Each colored line represents a different seed, which varies from 1 to 30

Table 3 Obtained breakwater parameters

Parameter	Value
$\mathcal{S}_L$ (m)	≥ 100
$\mathcal{S}_B$ (m)	≥ 100
K_t	≥ 0.5
L (m)	5
B (m)	300
T (m)	5

5 Conclusion

This study fills a gap in the literature concerning the computation of the wave transmission coefficient (K_t) for 3D box-type FBs, as most existing research focuses on 2D

configurations. Numerical models based on potential flow theory were used to evaluate the K_t of a 3D box-type floating breakwater designed to protect other offshore structures.

Our findings indicate that, contrary to 2D scenarios, 3D analysis reveals multiple K_t levels for a given case. In addition, at a $K_{t_{max}}$, variations in K_t within the WSZ occurs due to destructive and constructive interferences of scattered waves. Furthermore, while conventional floating offshore structures feature regular waterplane shapes, 3D WSZs exhibit tooth-like and Christmas tree-like shapes. The results further suggest that higher relative breakwater beam ratios yield convergent mean K_t , highlighting the importance of beam ratio in determining the breakwater's performance. We also observed an exponential relationship between the wave-shelter area and the K_t levels, with larger beam ratios leading to even lower K_t values and enhanced wave protection.

Furthermore, we demonstrated the practical application of these findings by using ML techniques to predict the wave-shelter area and optimize breakwater dimensions. This approach enables a cost-effective design strategy that ensures adequate wave attenuation for a one MW-peak floating solar photovoltaic system.

Despite the comprehensive analysis, the current research presents several constraints: 1) it focuses on the 3D K_t and the wave-shelter area generated by a FB, rather than other factors, such as wave-induced forces; 2) it employs a potential flow theory, which may not fully capture viscous effects or wave-breaking phenomena observed in real-world scenarios; 3) it is limited to regular wave conditions, whereas irregular or spectral wave conditions would better represent actual ocean waves; 4) it examines box-type FBs, despite that other types of floating breakwater shapes exist. These constraints highlight potential directions for future studies.

In summary, this study advances the understanding of K_t for 3D floating breakwaters, underscoring the considerable influence of breakwater dimensions and wave conditions on the sheltered area. These insights are crucial for designing effective wave protection solutions for offshore structures.

Appendix A: Dimensional analysis

Here, we are interested in obtaining parameters that may influence the K_t value for our 3D case through dimensional analysis. Thus, consider the following variables for the fixed breakwater problem:

L - Breakwater length	h - Water depth
B - Breakwater beam	g - Gravitational acceleration
T - Breakwater draft	ρ - Water density
λ - Wavelength	K_t - Wave transmission coefficient
T_w - Wave period	(x, y) - Position on the horizontal plane

It is well known that from the dispersion relation, we have $T_w = f(\lambda, h)$, and due to this dependence, T_w was neglected. Also, as we assumed an inviscid fluid, the bulk viscosity μ was not considered. Thus, we have the following dimensional table with $k = 3$ rows and $n = 10$ columns (consider values only):

	L	B	T	λ	h	g	ρ	K_t	x	y
M	0	0	0	0	0	0	1	0	0	0
L	1	1	1	1	1	1	-3	0	1	1
T	0	0	0	0	0	-2	0	0	0	0

Removing the spurious rows, we have $k' = 1$ rows and $n' = 8$ columns, which means that we will have Π_i groups, where $1 \leq i \leq (n' - k') \Rightarrow 1 \leq i \leq 7$, thus:

	L	B	T	λ	h	K_t	x	y
L	1	1	1	1	1	0	1	1

Choosing the following scale parameter $\mathbf{L} \equiv \lambda$, then:

Appendix B: Values of μ_{K_t} and σ_{K_t} for all cases

Table 4 Mean K_t values (μ_{K_t}) for different cases and $K_{t_{\max}}$ values

$L(\text{m})$	$B(\text{m})$	$T(\text{m})$	$\mu_{K_{t_{\max}}=0.1}$	$\mu_{K_{t_{\max}}=0.2}$	$\mu_{K_{t_{\max}}=0.3}$	$\mu_{K_{t_{\max}}=0.4}$	$\mu_{K_{t_{\max}}=0.5}$	$\mu_{K_{t_{\max}}=0.6}$	$\mu_{K_{t_{\max}}=0.7}$	$\mu_{K_{t_{\max}}=0.8}$	$\mu_{K_{t_{\max}}=0.9}$	$\mu_{K_{t_{\max}}=1.0}$
5	100	5	NA	NA	0.21	0.30	0.40	0.50	0.57	0.62	0.64	0.66
25	100	5	NA	NA	0.20	0.31	0.40	0.50	0.57	0.62	0.64	0.66
5	500	5	NA	NA	0.16	0.20	0.25	0.28	0.31	0.33	0.36	0.38
25	500	5	NA	NA	0.17	0.21	0.27	0.30	0.32	0.35	0.37	0.39
5	100	25	NA	NA	0.22	0.31	0.40	0.49	0.56	0.60	0.62	0.65
25	100	25	NA	NA	0.22	0.31	0.40	0.49	0.56	0.60	0.62	0.65
5	500	25	NA	NA	0.16	0.20	0.24	0.26	0.29	0.32	0.34	0.36
25	500	25	NA	NA	0.16	0.20	0.24	0.26	0.29	0.32	0.34	0.36
5	100	5	NA	NA	NA	NA	NA	0.53	0.61	0.73	0.86	0.89
25	100	5	NA	NA	0.21	0.30	0.39	0.48	0.59	0.68	0.70	0.72
5	500	5	NA	NA	NA	NA	0.47	0.54	0.57	0.63	0.68	0.69
25	500	5	0.07	0.18	0.22	0.27	0.31	0.35	0.37	0.38	0.39	0.39
5	100	25	NA	NA	NA	0.32	0.41	0.50	0.61	0.70	0.75	0.78
25	100	25	NA	NA	NA	0.31	0.40	0.50	0.61	0.70	0.74	0.77
5	500	25	NA	0.14	0.20	0.25	0.30	0.34	0.38	0.40	0.41	0.42
25	500	25	NA	0.14	0.20	0.25	0.30	0.34	0.37	0.39	0.40	0.41
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	0.87	0.97
25	100	5	NA	0.12	0.18	0.25	0.36	0.47	0.59	0.71	0.79	0.81
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	0.87	0.92
25	500	5	0.06	0.10	0.15	0.22	0.30	0.33	0.36	0.41	0.44	0.46
5	100	25	NA	NA	NA	NA	NA	0.53	0.62	0.73	0.81	0.82
25	100	25	NA	NA	NA	0.33	0.41	0.51	0.61	0.73	0.79	0.80

$$\begin{aligned}
 \Pi_1 &= L\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_1 = L/\lambda \\
 \Pi_2 &= B\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_2 = B/\lambda \\
 \Pi_3 &= T\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_3 = T/\lambda \\
 \Pi_4 &= h\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_4 = h/\lambda \\
 \Pi_5 &= K_t\lambda^\alpha \Rightarrow \alpha = 0 \Rightarrow \Pi_5 = K_t \\
 \Pi_6 &= x\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_6 = x/\lambda \\
 \Pi_7 &= y\lambda^\alpha \Rightarrow \alpha = -1 \Rightarrow \Pi_7 = y/\lambda
 \end{aligned} \tag{28}$$

where L/λ is the relative breakwater length, B/λ is the relative breakwater beam, T/λ is the relative breakwater draft, h/λ is the relative water depth, and x/λ and y/λ give the relative position. Thus, we have that the K_t values will depend on the following variables:

$$K_t = f(L, B, T, h, x, y, \lambda) \tag{29}$$

Furthermore, for the 2D case, it is well known that:

$$K_t = f(L, T, h, \lambda) \tag{30}$$

5	500	25	NA	0.13	0.20	0.30	0.36	0.42	0.48	0.50	0.51	0.51
25	500	25	NA	0.14	0.21	0.27	0.32	0.35	0.38	0.41	0.42	0.43
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.99
25	100	5	NA	NA	NA	NA	NA	NA	0.62	0.72	0.86	0.92
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.96
25	500	5	NA	NA	NA	NA	0.47	0.52	0.57	0.61	0.65	0.68
5	100	25	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.92
25	100	25	NA	NA	NA	NA	NA	NA	0.66	0.75	0.84	0.89
5	500	25	NA	NA	0.25	0.32	0.37	0.54	0.59	0.64	0.69	0.70
25	500	25	NA	0.14	0.20	0.28	0.38	0.44	0.47	0.49	0.50	0.50
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.99
25	100	5	NA	NA	NA	NA	NA	NA	NA	NA	0.85	0.97
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.98
25	500	5	NA	NA	NA	NA	NA	NA	NA	0.77	0.83	0.85
5	100	25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	100	25	NA	NA	NA	NA	NA	NA	NA	NA	0.89	0.96
5	500	25	NA	NA	NA	NA	NA	NA	NA	0.71	0.82	0.88
25	500	25	NA	0.11	0.16	0.24	0.35	0.50	0.57	0.64	0.69	0.69

Table 5 Standard deviations (σ_{K_t}) of K_t for different cases and $K_{t_{max}}$ values

$L(m)$	$B(m)$	$T(m)$	$\sigma_{K_{t_{max}} = 0.1}$	$\sigma_{K_{t_{max}} = 0.2}$	$\sigma_{K_{t_{max}} = 0.3}$	$\sigma_{K_{t_{max}} = 0.4}$	$\sigma_{K_{t_{max}} = 0.5}$	$\sigma_{K_{t_{max}} = 0.6}$	$\sigma_{K_{t_{max}} = 0.7}$	$\sigma_{K_{t_{max}} = 0.8}$	$\sigma_{K_{t_{max}} = 0.9}$	$\sigma_{K_{t_{max}} = 1.0}$
5	100	5	NA	NA	0.07	0.09	0.10	0.10	0.11	0.12	0.13	0.15
25	100	5	NA	NA	0.08	0.09	0.09	0.10	0.11	0.12	0.13	0.15
5	500	5	NA	NA	0.07	0.10	0.13	0.16	0.18	0.20	0.23	0.25
25	500	5	NA	NA	0.07	0.10	0.13	0.15	0.18	0.19	0.22	0.24
5	100	25	NA	NA	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.16
25	100	25	NA	NA	0.07	0.08	0.10	0.10	0.11	0.13	0.14	0.16
5	500	25	NA	NA	0.07	0.10	0.13	0.15	0.18	0.20	0.22	0.25
25	500	25	NA	NA	0.07	0.10	0.13	0.15	0.18	0.20	0.23	0.25
5	100	5	NA	NA	NA	NA	NA	0.05	0.07	0.08	0.05	0.06
25	100	5	NA	NA	0.06	0.08	0.10	0.11	0.11	0.11	0.11	0.13
5	500	5	NA	NA	NA	NA	0.02	0.05	0.07	0.10	0.13	0.14
25	500	5	0.03	0.06	0.06	0.08	0.10	0.13	0.14	0.16	0.17	0.18
5	100	25	NA	NA	NA	0.07	0.09	0.09	0.10	0.09	0.10	0.11
25	100	25	NA	NA	NA	0.08	0.09	0.10	0.10	0.09	0.10	0.12
5	500	25	NA	0.05	0.07	0.09	0.12	0.14	0.17	0.18	0.19	0.20
25	500	25	NA	0.05	0.07	0.09	0.12	0.14	0.17	0.18	0.19	0.20
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	0.02	0.02
25	100	5	NA	0.02	0.07	0.09	0.11	0.12	0.12	0.10	0.09	0.10
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	0.02	0.04
25	500	5	0.02	0.05	0.08	0.11	0.16	0.17	0.19	0.22	0.24	0.25
5	100	25	NA	NA	NA	NA	NA	0.06	0.07	0.07	0.08	0.08

25	100	25	NA	NA	NA	0.06	0.08	0.09	0.09	0.09	0.08	0.09
5	500	25	NA	0.05	0.08	0.09	0.10	0.12	0.14	0.16	0.16	0.17
25	500	25	NA	0.05	0.07	0.09	0.11	0.13	0.16	0.18	0.19	0.20
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.01
25	100	5	NA	NA	NA	NA	NA	NA	0.04	0.06	0.05	0.05
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.02
25	500	5	NA	NA	NA	NA	0.02	0.05	0.07	0.10	0.13	0.15
5	100	25	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.06
25	100	25	NA	NA	NA	NA	NA	NA	0.06	0.06	0.05	0.06
5	500	25	NA	NA	0.05	0.07	0.08	0.08	0.08	0.11	0.13	0.13
25	500	25	NA	0.05	0.07	0.09	0.11	0.12	0.13	0.15	0.16	0.16
5	100	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.00
25	100	5	NA	NA	NA	NA	NA	NA	NA	NA	0.02	0.02
5	500	5	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.01
25	500	5	NA	NA	NA	NA	NA	NA	NA	0.02	0.04	0.06
5	100	25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	100	25	NA	NA	NA	NA	NA	NA	NA	NA	0.02	0.03
5	500	25	NA	NA	NA	NA	NA	NA	NA	0.04	0.05	0.08
25	500	25	NA	0.03	0.05	0.10	0.13	0.12	0.12	0.13	0.14	0.14

Appendix C: Sheltered area dimensions

Table 6 Sheltered length and beam for different cases and $K_{t_{\max}}$ values

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.3	100	5	5	25	118.7	30.7
0.4	100	5	5	25	155.7	37.3
0.5	100	5	5	25	225.7	51.3
0.6	100	5	5	25	376.7	79.3
0.7	100	5	5	25	795.7	100
0.8	100	5	5	25	1982.3	100
0.9	100	5	5	25	1972	100
1.0	100	5	5	25	1969.7	100
0.3	100	25	5	25	119.3	30.7
0.4	100	25	5	25	151	37.3
0.5	100	25	5	25	211	51.3
0.6	100	25	5	25	348.7	86.7
0.7	100	25	5	25	761	100
0.8	100	25	5	25	1968.3	100
0.9	100	25	5	25	1972	100
1.0	100	25	5	25	1971.3	100
0.3	500	5	5	25	1701	226.7
0.4	500	5	5	25	1999.7	275.3

Table 6 Sheltered length and beam for different cases and $K_{t_{\max}}$ values (continued)

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.5	500	5	5	25	1999.7	373.3
0.6	500	5	5	25	1999.7	492.7
0.7	500	5	5	25	1994.3	500
0.8	500	5	5	25	1986	500
0.9	500	5	5	25	1969.7	500
1.0	500	5	5	25	1969.7	500
0.3	500	25	5	25	1618.3	212.7
0.4	500	25	5	25	1932.3	254.7
0.5	500	25	5	25	1797.7	401.3
0.6	500	25	5	25	1978.7	500
0.7	500	25	5	25	1975.3	500
0.8	500	25	5	25	1982.3	500
0.9	500	25	5	25	1976.7	500
1.0	500	25	5	25	1969.7	500
0.3	100	5	25	25	104.3	30.7
0.4	100	5	25	25	152	37.3
0.5	100	5	25	25	236.3	58.7
0.6	100	5	25	25	443.3	86.7
0.7	100	5	25	25	987.7	100
0.8	100	5	25	25	1982.3	100

Table 6 Sheltered length and beam for different cases and $K_{\max}$ values (continued)

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.5	500	5	5	25	1999.7	373.3
0.9	100	5	25	25	1979	100
1.0	100	5	25	25	1969.7	100
0.3	100	25	25	25	108.7	30.7
0.4	100	25	25	25	154.7	37.3
0.5	100	25	25	25	242.7	58.7
0.6	100	25	25	25	450.7	86.7
0.7	100	25	25	25	1004	100
0.8	100	25	25	25	1972	100
0.9	100	25	25	25	1968.3	100
1.0	100	25	25	25	1965	100
0.3	500	5	25	25	1673	233.3
0.4	500	5	25	25	1999.7	296.7
0.5	500	5	25	25	1999.7	429.3
0.6	500	5	25	25	1999.7	499.3
0.7	500	5	25	25	1989.3	500
0.8	500	5	25	25	1971.7	500
0.9	500	5	25	25	1973	500
1.0	500	5	25	25	1969.7	500
0.3	500	25	25	25	1682	233.3
0.4	500	25	25	25	1990.7	303.3
0.5	500	25	25	25	1990.7	436.7
0.6	500	25	25	25	1989.7	499.3
0.7	500	25	25	25	1982.3	500
0.8	500	25	25	25	1964.7	500
0.9	500	25	25	25	1972	500
1.0	500	25	25	25	1968.7	500
0.5	100	5	5	75	38.7	33.3
0.6	100	5	5	75	80.3	47.3
0.7	100	5	5	75	147.7	61.3
0.8	100	5	5	75	292.3	75.3
0.9	100	5	5	75	1112.3	100
1.0	100	5	5	75	1969.7	100
0.3	100	25	5	75	22.7	70
0.4	100	25	5	75	79	89.3
0.5	100	25	5	75	167.7	100
0.6	100	25	5	75	325.7	100
0.7	100	25	5	75	708	100
0.8	100	25	5	75	1789	100
0.9	100	25	5	75	1969.7	100
1.0	100	25	5	75	1970.7	100
0.4	500	5	5	75	289.7	19.3
0.5	500	5	5	75	1088	75.3
0.6	500	5	5	75	1995	187.3
0.7	500	5	5	75	1999.7	271.3

Table 6 Sheltered length and beam for different cases and $K_{\max}$ values (continued)

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.8	500	5	5	75	1999.7	425.3
0.9	500	5	5	75	1999.7	500
1.0	500	5	5	75	1969.8	500
0.1	500	25	5	75	103.3	61.3
0.2	500	25	5	75	321	173.3
0.3	500	25	5	75	245	439.3
0.4	500	25	5	75	801.3	439.3
0.5	500	25	5	75	1200	495.3
0.6	500	25	5	75	1984.3	500
0.7	500	25	5	75	1975.7	500
0.8	500	25	5	75	1969.7	500
0.9	500	25	5	75	1979	500
1.0	500	25	5	75	1976	500
0.4	100	5	25	75	19	47.3
0.5	100	5	25	75	43.3	61.3
0.6	100	5	25	75	91.3	61.3
0.7	100	5	25	75	212	75.3
0.8	100	5	25	75	661.7	100
0.9	100	5	25	75	1992.3	100
1.0	100	5	25	75	1987	100
0.4	100	25	25	75	0.1	61.3
0.5	100	25	25	75	55	61.3
0.6	100	25	25	75	119.3	75.3
0.7	100	25	25	75	264.7	21.4
0.8	100	25	25	75	761.7	100
0.9	100	25	25	75	1983.7	100
1.0	100	25	25	75	1970.7	100
0.2	500	5	25	75	236	75.3
0.3	500	5	25	75	822.3	159.3
0.4	500	5	25	75	1328.3	215.3
0.5	500	5	25	75	1999.7	327.3
0.6	500	5	25	75	1999.7	453.3
0.7	500	5	25	75	1984	500
0.8	500	5	25	75	1979	500
0.9	500	5	25	75	1976.3	500
1.0	500	5	25	75	1969.7	500
0.2	500	25	25	75	127.3	145.3
0.3	500	25	25	75	748.3	145.3
0.4	500	25	25	75	1296.7	229.3
0.5	500	25	25	75	1995	341.3
0.6	500	25	25	75	1995	453.3
0.7	500	25	25	75	1970.7	500
0.8	500	25	25	75	1975.7	500
0.9	500	25	25	75	1969.7	500
1.0	500	25	25	75	1969.6	500

Table 6 Sheltered length and beam for different cases and K_{max} values (continued)

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.9	100	5	5	150	164	66.7
1.0	100	5	5	150	1992.3	100
0.2	100	25	5	150	22.7	22.7
0.3	100	25	5	150	63.3	38.7
0.4	100	25	5	150	88.3	66.7
0.5	100	25	5	150	118.3	94.7
0.6	100	25	5	150	244	94.7
0.7	100	25	5	150	457.7	94.7
0.8	100	25	5	150	1024.3	100
0.9	100	25	5	150	1992.3	100
1.0	100	25	5	150	1975	100
0.9	500	5	5	150	1999.7	262.7
1.0	500	5	5	150	1987.3	500
0.1	500	25	5	150	329.9	80.8
0.2	500	25	5	150	644.1	157.8
0.3	500	25	5	150	778	190.6
0.4	500	25	5	150	1999.7	290.7
0.5	500	25	5	150	1999.7	346.7
0.6	500	25	5	150	1999.7	402.7
0.7	500	25	5	150	1999.7	486.7
0.8	500	25	5	150	1992.3	500
0.9	500	25	5	150	1975	500
1.0	500	25	5	150	1987.3	500
0.7	100	5	25	150	0.1	100
0.8	100	5	25	150	105.3	100
0.9	100	5	25	150	634.3	100
1.0	100	5	25	150	1974.7	100
0.5	100	25	25	150	33	88.7
0.6	100	25	25	150	68	94.7
0.7	100	25	25	150	143.3	94.7
0.8	100	25	25	150	382.7	100
0.9	100	25	25	150	1904.3	100
1.0	100	25	25	150	1975	100
0.2	500	5	25	150	256.5	62.9
0.3	500	5	25	150	457.7	94.7
0.4	500	5	25	150	538.3	178.7
0.5	500	5	25	150	722	206.7
0.6	500	5	25	150	1049	290.7
0.7	500	5	25	150	1916.7	486.7
0.8	500	5	25	150	1975	500
0.9	500	5	25	150	1979.7	500
1.0	500	5	25	150	1987.7	500
0.2	500	25	25	150	80.7	94.7
0.3	500	25	25	150	148.3	318.7

Table 6 Sheltered length and beam for different cases and K_{max} values (continued)

K_t (m)	B (m)	L (m)	T (m)	λ (m)	$\mathcal{S}_L$ (m)	$\mathcal{S}_B$ (m)
0.4	500	25	25	150	915.7	234.7
0.5	500	25	25	150	1544.7	318.7
0.6	500	25	25	150	1992.3	402.7
0.7	500	25	25	150	1979.7	500
0.8	500	25	25	150	1992.3	500
0.9	500	25	25	150	1975	500
1.0	500	25	25	150	1979.7	500
1.0	100	5	5	300	1999.7	100
0.7	100	25	5	300	28	28
0.8	100	25	5	300	81	82.7
0.9	100	25	5	300	485.7	100
1.0	100	25	5	300	1979.7	100
1.0	500	5	5	300	1999.7	433.3
0.6	500	25	5	300	708.3	83.3
0.7	500	25	5	300	1765.3	153.3
0.8	500	25	5	300	1999.7	293.3
0.9	500	25	5	300	1999.7	433.3
1.0	500	25	5	300	1969.7	500
0.9	100	25	25	300	75.7	100
1.0	100	25	25	300	1969.7	100
0.8	500	5	25	300	87.3	83.3
0.9	500	5	25	300	290.7	223.3
1.0	500	5	25	300	503.7	500
0.3	500	25	25	300	61.3	48.7
0.4	500	25	25	300	182.3	118.7
0.5	500	25	25	300	253.5	62.1
0.6	500	25	25	300	642.3	258.7
0.7	500	25	25	300	1038.3	328.7
0.8	500	25	25	300	1999.7	433.3
0.9	500	25	25	300	1980.3	500
1.0	500	25	25	300	1987.7	500
1.0	100	5	5	600	1970	100
1.0	100	25	5	600	1970	100
1.0	500	5	5	600	1999.7	377.3
0.9	500	25	5	600	1240.7	237.3
1.0	500	25	5	600	1999.7	447.3
1.0	100	5	25	600	0.1	100
1.0	100	25	25	600	1969.7	100
1.0	500	5	25	600	179.3	236.7
0.9	500	25	25	600	383.7	236
1.0	500	25	25	600	1999.7	500

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